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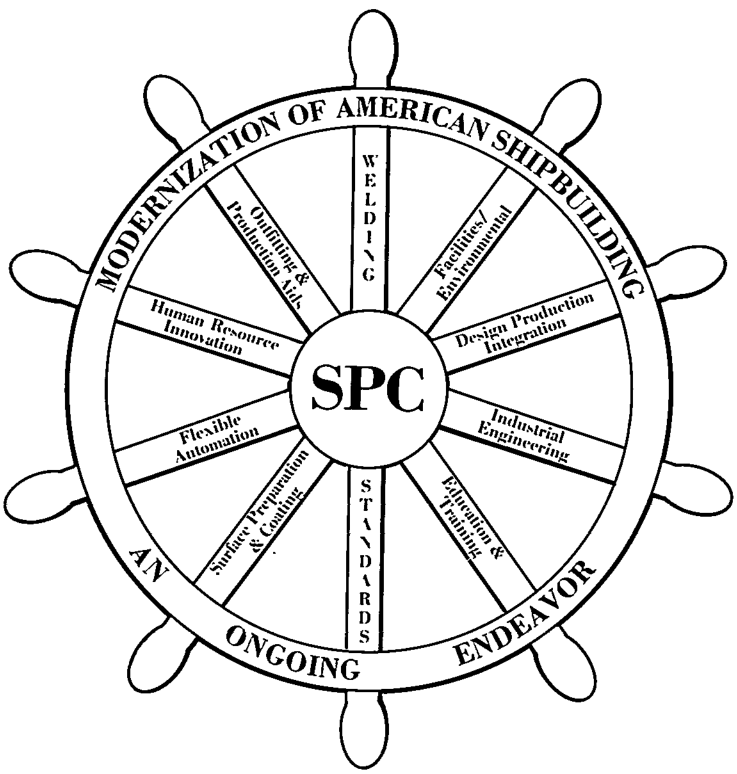

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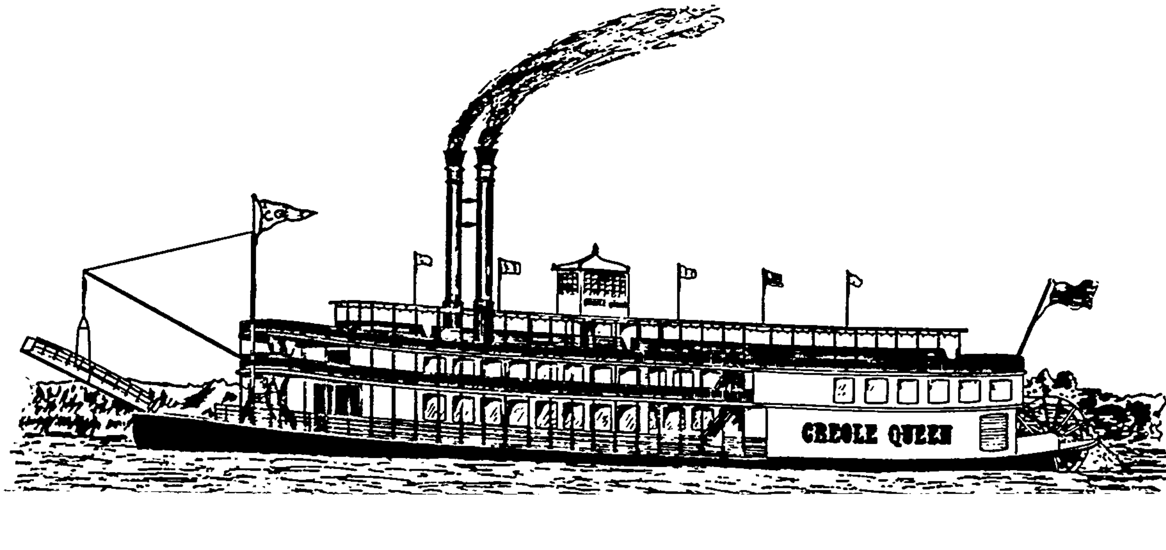

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The Application of Intelligent Robotic Systems and Lasers for Manufacturing

No. 7

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ABSTRACT

The R&D programs in Manufacturing Technology at The Pennsylvania State University have a major emphasis on automation of materials processing and inspection. Two on-going research projects in these areas, that are based on the application of laser technology are (1) the Laser Articulated Robotic System (LARS), and (2) the Intelligent Robot Inspection System (IRIS). Both of these projects are supported by the U.S. Navy Manufacturing Technology Program.

The paper presents the background, current status, research results, and future plans for the LARS and IRIS.

INTRODUCTION

The application of lasers in manufacturing have been limited due to the requirements that the workpiece must be moved under a fixed beam. This process is time consuming because extensive fixturing and alignment are required to assure that the laser beam contacts the part at the proper position and orientation for the process involved.

Advances in sensor and control technology have made it possible to manipulate laser beams in space along a precise path using robots. This development has created a surge of interest in the application of lasers for materials processing and inspection, Reference 1. Accordingly, the Manufacturing Science Program has been established by the Applied Research Laboratory at The Pennsylvania State University to develop solutions to the unique problems associated with precision fabrication and inspection of components for surface and underwater vehicles.

The development of advanced welding technology for manufacturing and repair was planned to initially demonstrate the applicability of laser technology for materials processing, welding and cutting of thick sections, and then to develop articulating robotics and associated technology for controlled high speed manipulation of a laser beam throughout a large manufacturing cell.

The major thrusts of the Manufacturing Science Program is the development of equipment for automated materials processing and inspection. This requires the use of robots coupled with high powered (up to 25 kw) continuous wave CO_2 lasers for welding, cutting, heat treating, cladding, transformation hardening and glazing, and solid state lasers for measurement, References 1-7. For laser materials processing, the Laser Articulated Robotic System (LARS) is being developed. This is a large robot which, when interfaced with a high power laser, provides the capability for manipulating a beam over large distances, focusing the beam to a small spot to concentrate the energy for welding, cutting, or a larger configuration for other processes. For precision measurement, the Intelligent Robotic Inspection System (IRIS), is being developed. This is a large gantry robot equipped with laser based vision systems for precision space location and part profiling. Both these projects are funded by the U.S. Navy Manufacturing Technology Program.

In order to expand the application and acceptance of laser technology for materials processing, a survey was conducted to assess the applicability of high power lasers in manufacturing for the Navy and Army as well as for the aerospace, electric utility, automotive, and pipeline industries, Reference 8. Copies of this survey report are available upon request.

The paper presents the background, current status, research results, and future plans for the LARS and IRIS, and is organized in five main sections. Descriptions of the LARS and

IRIS projects are provided in Sections 2 and 3, respectively. Each of these two sections are, in turn, divided into several subsections. Future plans for both LARS and IRIS projects are discussed in Section 4. Summary and conclusions are presented in Section 5.

LASER ARTICULATED ROBOTIC SYSTEM (LARS)

The LARS program had its beginning in 1982 by identifying the requirements for a laser beam delivery system which later evolved into specifications for a subsequent request for proposal. The requirements are summarized in Figure 1. A contract was awarded for the development of the LARS

IMPORTANT PARAMETERS FOR LARS/LARS SR.

RANGE OF OPERATION:	11 FT x 11 FT x 3 FT 20 FT x 20 FT x 10 FT
MODES OF OPERATION:	MANUAL TEACH OFFLINE PROGRAM AUTOMATIC
TRACKING PRECISION:	ALONG SEAM ± 0.005 IN VERTICAL ± 0.015 IN ANGULAR CONTROL ± 1°
WELDING/CUTTING SPEEDS:	0-200 IN/MIN
TRACKING DEVICE:	NON-CONTACTING 200 Hz SAMPLING SPEED CLOSED LOOP REAL TIME
CAPABILITIES:	WELDING, CUTTING, HEAT TREATING, CLADDING, SURFACE TRANSFORMATION HARDENING

Figure 1

in August 1983. The contract is divided into five phases: conceptual design, final design, system fabrication, installation and operator training, and acceptance testing. The program is currently in the fabrication phase with completion scheduled for March 1987. Upon completion the LARS will be delivered to the Westinghouse Research and Development Center in Pittsburgh and interfaced with a 15 kw CO_2 continuous wave laser for technology demonstration and transfer.

The LARS is shown in Figure 2 in its current state of development. When completed it will consist of six major subsystems including the robot, beam transport, workhead, vision, electronic control, and software. These subsystems and their components are shown in Figure 3. The principal components are described below.

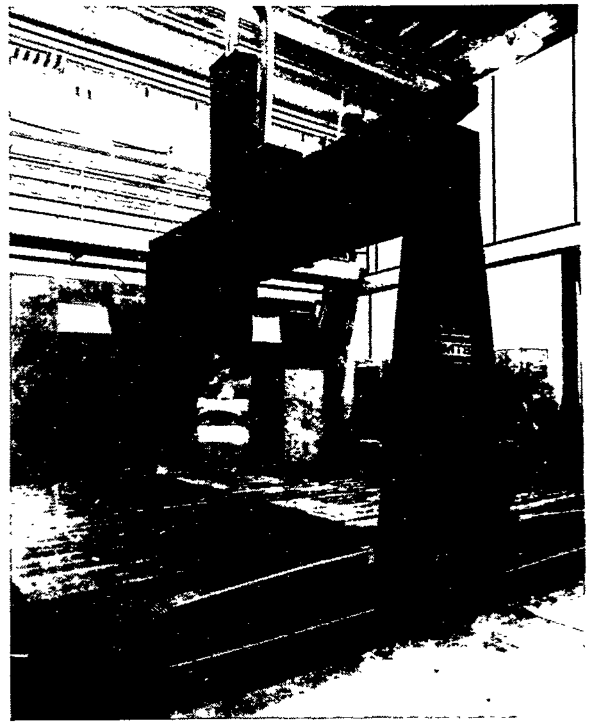


Figure 2

LARS SUBSYSTEM BREAKDOWN

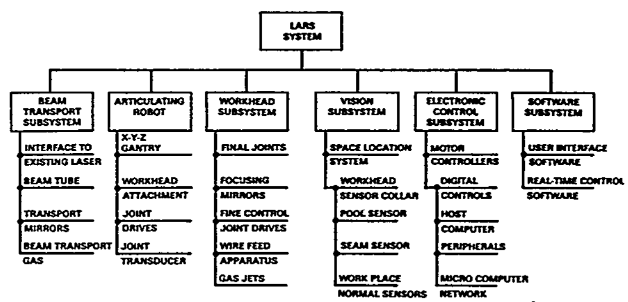


Figure 3

Robot Subsystem

After considering all robot configurations, it was determined that a gantry based system was the only practical structure for this application. The initial requirement was for a system having a reach of 20 feet x 20 feet x 10 feet. To reduce the costs a prototype system will be developed first. This system will have a working volume for welding in the down-hand position of 14 feet x 14 feet x 3 feet. The gantry provides x, y, and z translation of the beam, and an articulated arm located at the lower end of the Z-axis provides the remaining degrees of freedom required to meet the requirements for random path welding and cutting. The gantry system was designed specifically for LARS since a commercially available robot meeting the requirements established for this system could not be found. The robot is designed to be as accurate as current technology permits, however, the accuracy requirements shown in Figure 1 are dynamic rather than point-to-point and relate to the position of the focused

beam instead of the robot position. As a result, the beam positioning accuracy is obtained by a carefully controlled positioning mirror coordinated with a high speed vision system located in the workhead.

Workhead Subsystem

The workhead is attached to the lower end of the Z-axis of the gantry. The workhead shown in Figure 4 is an integrated system of mechanical and electromechanical components which focuses the laser beam and provides final positioning of the laser beam and process hardware at the workpiece. The workhead focuses the laser beam to a 0.040-inch diameter spot for welding and cutting using f/7 optics. In addition to focusing and beam positioning optics, the workhead contains a gas shield for plasma suppression, wire feeder and positioner, seam tracking vision components, and a gas cutting jet. While the vision system is integrated with the workhead, it is so important to the success of LARS, it will be discussed in the next section.

Vision System

The positioning requirements for the LARS include, tracking the center of a butt joint to an accuracy of ± 0.005 inches, maintaining the desired standoff distance to within 0.015 inches, and controlling the angle of the incident beam with respect to the workpiece to $90^{\circ} \pm 1^{\circ}$. Further, this tracking requirement must be met for random path welds throughout the working envelope without preprogramming, while operating at speeds of 200 inches per minute. For metalworking processes other than welding where there is no seam to follow, the specification requires that LARS follow a preprogrammed path to the same accuracies as that stated for welding.

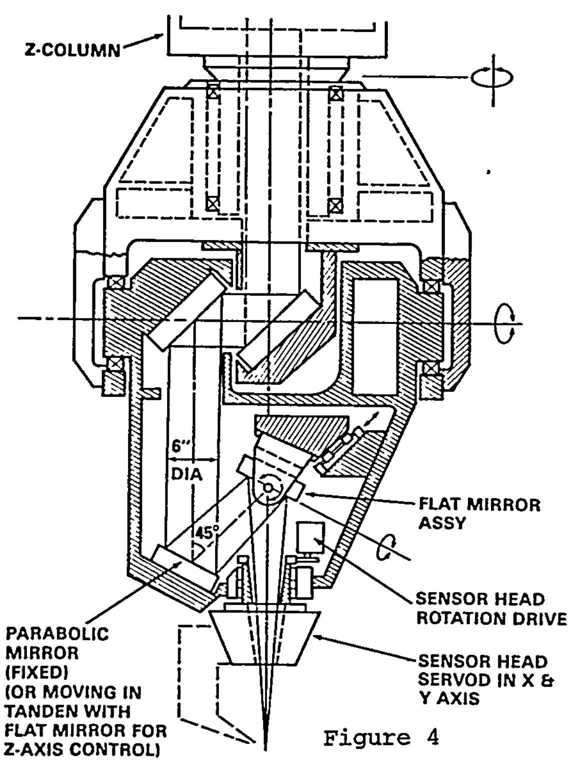
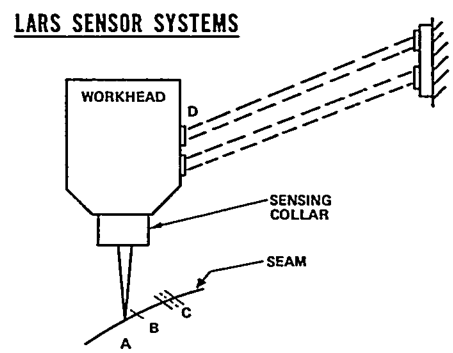


Figure 4

The LARS vision system incorporates four vision subsystems to meet the requirements for seam following and space location. For seam following the two independent closed loop systems, fine loop and coarse loop, are utilized. The sensors and their function are shown schematically in Figure 5. The A sensor uses three linear CCD's to monitor the x, y, and z coordinates of the laser spot at the surface of the workpiece and measures the workpiece surface angle. The output of Sensor A, combined with the fine control mirror drives, provides the precision positioning of the focused laser beam.



NAME	FUNCTION
A. BEAM SENSOR	LOCATES PUDDLE CENTER IN X, Y, Z
B. IN-CLOSE SEAM TRACKER	LOCATES SEAM Y POSITION DIRECTLY IN FRONT OF PUDDLE
C. LOOK-AHEAD SEAM TRACKER	LOCATES SEAM COORDINATES AND ANGLES ABOUT 2 INCHES IN FRONT OF PUDDLE
D. SPACE LOCATION SYSTEM	LOCATES POSITION OF WORKHEAD IN WORLD COORDINATE SYSTEM

Figure 5

Sensor B measures the y coordinate of the seam at three locations starting at 0.250 inches from the welding spot and spaced 0.750 inches apart. Sensor B finds the seam position by scanning an intense beam of light across the weld seam and monitoring the reflected light pattern. The beam scanning mechanism is an acousto-optic device which causes diffraction of the scanning laser beam when a RF signal is supplied to an acoustic transducer bonded to a crystal. By controlling the RF drive

frequency of the device, the angular position of the scanning laser beam and the beam position on the workpiece can be determined with precision. The solid state light deflector is the only technique which can create a complex pattern of light in the time available. An additional benefit of this approach is its flexibility. An acousto-optic deflector is completely programmable and can be programmed to generate any sequence of light patterns within the range of operation. Sensors A and B acquire data at a 1 kHz rate and update the fine position mirror controller at 200 Hz for seam tracking. For comparison, current seam tracking systems for arc welding operate at 30 Hz maximum. The information from these two sensor systems is obtained synchronously. The desired weld pool location determined by Sensor B is compared to the actual weld pool location from Sensor A. If these positions differ, an error signal is sent to the fine position mirror controller and a correction is made.

Sensor C is the workpiece profile sensor. It measures the angular orientation of the workpiece surfaces and collects coordinate data used to determine the shape and orientation of the part ahead of the welding area. This information is provided to the robot controller at a 50 Hz rate for course robot position control and to develop data to be used during the fine position control. Sensor C also uses solid state laser beam positioners in conjunction with linear CCD's.

The space location system Sensor D, locates and tracks the position of the workhead in world coordinates for those preprogrammed metalworking operations in which no seam is available for guidance. This system is required to maintain a knowledge of the position of the robot workhead to within 0.005 inches over the working volume. Since it is not possible to obtain such accuracy using robot joint encoders, a tracking interferometric system utilizing fixed interferometers in combination with retroreflectors mounted on the workhead was selected. This sensor system will be described in detail in the IRIS description.

<u>Control System</u>

The control system is comprised of the computer system and precision digital interface hardware and must be capable of:

- providing very effective control accuracy over extreme control ranges by processing fine seam tracker data and using it to coordinate the position of the focused laser spot with the movement of the gantry based robot.
- coordinating the motion of a complex, multi-degree of freedom, robot with trajectories programmed from a data base, or computed on-line.
- providing on-line compensation for variations in control characteristics resulting from a wide range of workhead motions and orientations which occur during operation.

To accomplish these tasks, a hierarchical multi-processor control system will be used. A VAX 11/750 will serve as the supervisory computer to manage task planning and machine coordination. Clusters of Motorola 68000 microprocessors will serve as intelligent subsystems. Loose coupling via communication links allows the supervisory computer to control, monitor, or coordinate the operation of each multi-processor cluster.

Using this concept, the LARS control system tasks are partitioned into six subsections.:

- operator interface and system management
- coarse loop control
- coordinate conversion and servo control
- fine loop control
- safety
- task support

The tasks in each subsection will be accomplished by either one computer system or a cluster of microcomputers. Selection of a particular computer or use of special purpose hardware and software modules can be specified to suit critical or unique tasks to be performed by a particular subsection.

INTELLIGENT ROBOTIC INSPECTION SYSTEM (IRIS)

The Applied Research Laboratory has been actively involved in the design and inspection of multi-blade propulsors for underwater vehicles for many years. Unfortunately, due to the complex shape and limited space between blades, the inspection equipment can only measure to an accuracy of ± 0.003 inches. As a result, it has not been possible to establish a relationship between manufacturing accuracy and performance. Recognizing this need, the Navy has decided to develop the Intelligent Robotic Inspection System (IRIS), which will utilize the enhanced vision and control technology that has already been developed for the LARS

project. The contract was awarded for IRIS in January 1985 and is scheduled for delivery in December 1986.

The IRIS is essentially a robotic, laser based measuring system which will be capable of comparing actual part dimensions with design requirements to an accuracy of ±0.0005 inches. The system will be interfaced with a Computer Aided Design (CAD) system for state-of-the-art data retrieval and programming. The major technology issues which must be addressed include world coordinate and orientation measurement, non-contact part sensing, advanced robot control development, advanced user interface capabilities, and dynamic accuracy.

The IRIS is shown schematically in Figure 6. The system will consist of three major components including the mechanical, sensor, and control subsystems. These principal components will be described in the following sections.

Mechanical Subsystem

The primary mechanical components of the IRIS include the robot, a two-degree of freedom wrist assembly, the retroreflector, a granite base, a rotary table, and the robot end effector.

In contrast to the LARS, the IRIS robot will be a commercially available gantry system which provides x, y, and z translation. A highly repeatable, two-degree of freedom wrist assembly is located at the end of the Z-axis column of the robot. This wrist assembly is identical to the ones found on the more accurate coordinate measuring machines except the measuring component has been replaced with a specially designed end effector for part profiling. The retroreflector is also located on the Z-axis column. It is part of the space location system and consists of three mirror assemblies which serve to return the beam back to its source along a parallel path. The base of the IRIS will be constructed of granite to insure dimensional stability during the inspection process. Finally, a precision rotary table will be mounted on the granite base extending the effective measurement range from the original 3 foot x 3 foot x 3 foot measurement volume permitting the inspection of objects as large as 5 feet in diameter and 3 feet high.

Sensor Subsystem

In conventional measuring systems the measurement accuracy is functionally connected to the control accuracy. Since the control accuracy, which determines the accuracy of the robot or manipulation device is less than the measurement accuracy, the equipment can only be as accurate as the manipulation device for dynamic measurements. In the design of the IRIS, the measurement and control accuracy are functionally separated, therefore, the system accuracy can be as accurate as the measurement or

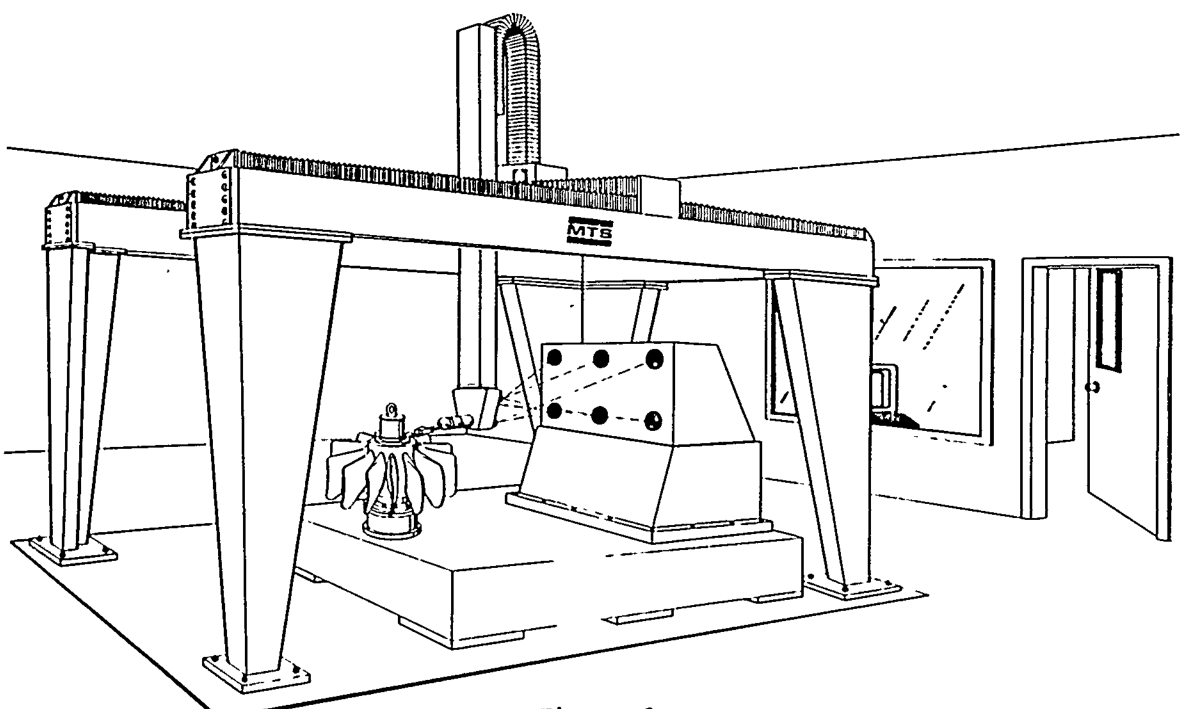


Figure 6

sensor accuracy and the accuracy can be obtained in the dynamic mode.

In order to meet the requirements for accuracy, two sensor subsystems, Figure 7, had to be developed for IRIS; the space location system (SLS), and the part sensor. The SLS consists of six laser interferometers located at one end of the granite table and three retroreflectors located on the Z-axis column. The SLS functions by measuring six distances to three points and then using this information, calculates the end effector position and orientation with respect to any predetermined coordinate system to an accuracy of 0.00025 inches.

The part sensor determines the position of the surface of the part with respect to the retroreflectors using the principle of laser triangulation for distance measurement. The part sensor shown schematically in Figure 8 consists of a solid state laser, optics, mirror, and a 3000 element linear array. The laser beam is focused by the optics, reflected to and from the part surface by the mirror, and distance measurements are determined by the position that the reflected laser beam strikes the linear array. Data is collected at a speed of 1000 Hz and the part sensor accuracy is projected to be 0.00025 inches. The part sensor is designed to pass between two propulsor blades and measure the distance normal to the part surface.

Control Subsystem

The IRIS control system has two major requirements. The system must be able to position the end effector within the work envelope with precision and the part sensor feedback must be used to monitor the location of the part being measured. In order to meet

IRIS
SENSOR SUBSYSTEM

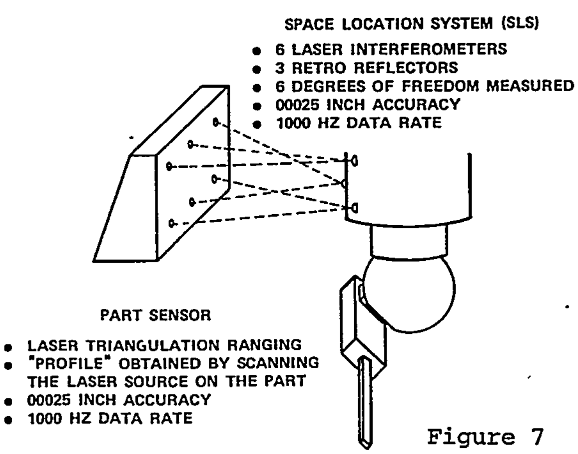
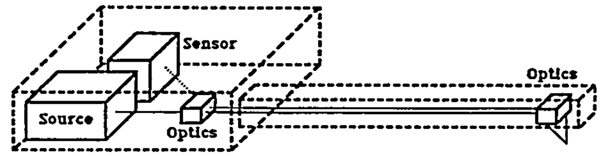
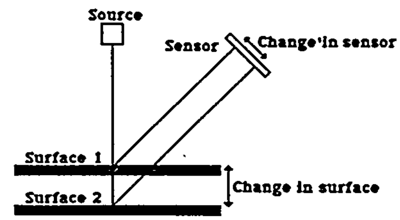


Figure 7



"Look-To-The-Side"
Triangulation Part Sensor



Triangulation Figure 8

these requirements, the control system uses two position locating devices; the SLS, and the motor resolvers. These signals are summed in order to form a composite feedback signal; one from the SLS at low frequencies, and one from the motor resolver at higher frequencies. This provides the control system with a broad range of frequency response, thereby extending the usable band width of the position control loop and improving the measurement speed and accuracy of dynamic response.

FUTURE DIRECTIONS

LARS related activities will continue in two directions; system refinement, and process development. After installation, the plan is to continue refining the system software and hardware. Equipment must be developed and integrated with the LARS which will permit coordinated control of the process parameters as well as the real time determination of weld quality. To improve autonomous functionalities of the LARS, its control system should be integrated with a knowledge-based system which is capable of making decisions in real time for high-speed laser welding, Reference 9. Additionally, new applications of laser technology must be developed for both the military and the private sector.

After installation and acceptance of the LARS at the Westinghouse Research and Development Center, the first application of this technology will be the welding of aircraft carrier launch rails to trough covers producing one-piece assemblies. This will require one and one-half inch deep welds in dissimilar materials. To assure that the work can proceed in a timely manner, Westinghouse is under

contract to The Pennsylvania State University to develop and demonstrate the process for welds which will meet Navy requirements for strength and straightness. Additionally, Westinghouse and The Pennsylvania State University have been developing the process requirements for other materials which are difficult to weld, such as, high strength steels, copper, and aluminum.

Future plans for the IRIS include hardware enhancement and applications of advanced inspection technology. It is desirable to increase the accuracy and work envelope of IRIS. Higher accuracy will permit the initiation of an applications oriented precision engineering program aimed at developing a direct relationship between precision, efficiency, and manufacturing cost. This program will also require the coupling with a knowledge-based system which could autonomously determine the location of the inspection points and the amount of data required for the inspection accuracy desired.

While the IRIS is addressing a specific Navy problem, advanced multi-blade propulsor design and inspection, it is considered to be a generic inspection system capable of inspecting any part that fits within the work envelope and has a measurement data base. The IRIS will be installed in the Applied Research Laboratory, Garfield Thomas Water Tunnel facility in a "clean room" environment with precise temperature and humidity control. After installation and initial operation, an extensive program of technology transfer will be implemented.

SUMMARY AND CONCLUSION

The paper summarized the background, current status, results, and future plans for two laser technology-based research projects at the Applied Research Laboratory of The Pennsylvania State University. Both these projects, namely, the Laser Articulated Robotic System (LARS) and the Intelligent Robotic Inspection System (IRIS), are supported by the U.S. Navy Manufacturing Technology Program.

The LARS is designed for precise manipulation of high power (up to 25 kw) laser beams for welding, cutting, heat treating, cladding, surface transformation for a variety of materials including aluminum, high strength alloy steels, ceramics, and composites. Supporting research efforts include development of hardware and software for real time seam tracking, and knowledge-based systems for process planning and robot control. While the initial thrust of the LARS project was on the application of laser technology to materials processing, related technologies such as seam tracking, real time control of welding parameters, CAD/CAM interface development, and human factors will be applied to arc welding in the future.

The first application of the LARS is scheduled to be the welding of catapult launch rail trough covers and rails to produce one-piece assemblies for aircraft carriers. Other applications include component welding for ship fabrication, missile launching systems, cutting and welding of tank armor plate, and aircraft engine manufacturing.

The IRIS is a robotic, laser based measuring system which will have the capability for comparing actual component or assembly dimensions with design requirements to an accuracy of ± 0.0005 inch. The inspection system is designed to have a generic measuring capability, and can be operated either by direct digital data input or from a CAD data base which precisely defines the part. During operation, a space location system consisting of laser interferometers and retroreflectors will guide the robot end effector in a prescribed path around a stationary part. A series of end effectors that will utilize laser triangulation and touch probes are planned. The laser triangulation devices are needed where high speed and/or small clearance is a consideration.

The first application of the IRIS is scheduled to be the design and certification of components for underwater vehicles.

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